

Scientific Motivation for the Ross Island Meteorology Experiment (RIME)

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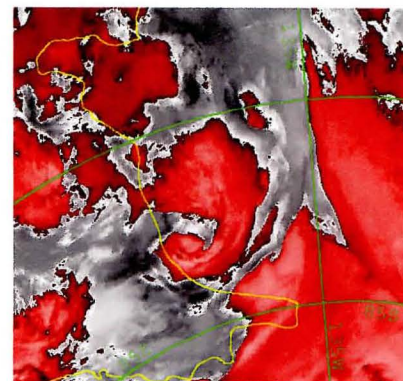
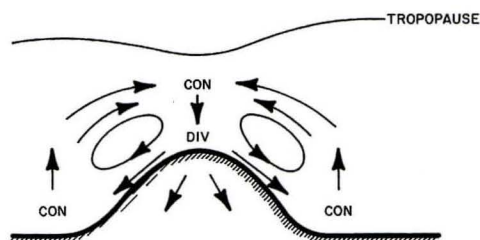
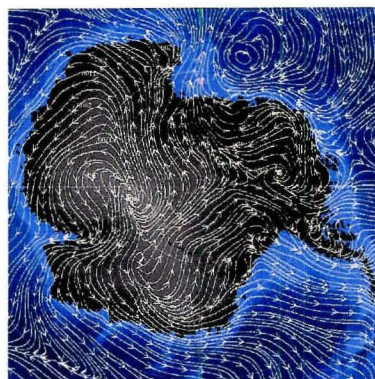
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1. Introduction

We are at the beginning of a new millennium, confronted by unprecedented environmental and climatic dilemmas. The past few decades have witnessed an increasing societal awareness of our natural environment and the potential impacts of human civilization on global weather and climate. Foremost among these issues is the prospect of global environmental change. Antarctic ozone depletion is a striking demonstration of the impact of human activities on nature. There is also the possibility of drastic sea level rises associated with melting of even a small fraction of the Antarctic ice masses. Most recently, attention has focused on the collapse of the Larsen B ice shelf, fueling speculation regarding the impact of global warming on the Antarctic ice budget. Although the validity of global change scenarios remains controversial, it has been established that the polar regions are sensitive indicators of global climate variability and change. In this respect, the Antarctic atmosphere remains an essential “test-tube” for meteorological processes as proposed by H. H. Lettau nearly 40 years ago.

Antarctica is the coldest and most remote continent on Earth. At a mean elevation of 2300 m, it is by far the highest continent as well. A permanent ice sheet that dominates the climate of the Antarctic atmosphere covers the entire continent. The continental area is 1.4 times that of the contiguous United States during austral summer but doubles in size during the winter due to growth of sea ice in the surrounding Southern Ocean. Nearly 75% of the world’s fresh water is held in the vast Antarctic ice sheets. Meteorological studies of the Antarctic atmosphere are relatively recent. Although valuable data sets were obtained during the heroic expeditions of the early 20th century, routine meteorological observations from Antarctica commenced only in 1957 with the International Geophysical Year. Approximately 30 stations were established in the Antarctic region, all but 6 were situated near the coast. Surface and upper air data taken at these stations provided the first comprehensive and systematic monitoring of the Antarctic atmosphere. Recently, staffed station data have been supplemented significantly by observations from automatic weather stations (AWS). Currently some 100 AWS exist over the Antarctic continent and, given the advances in design and reliability of the AWS, additional deployments are likely. In addition, an impressive stream of data is available from polar orbiting satellites. The ongoing development of satellite-borne instrumentation and enhancement of remote sensing capabilities ensure a more comprehensive observational database for the Antarctic atmosphere.

Antarctic meteorology is at an important crossroads. Recent technological advances in observing capabilities now permit the challenge of global change issues to be confronted. Integrated observing strategies including conventional staffed stations and upper air soundings, AWS networks, and satellite-derived data sets provide a wealth of data on the Antarctic atmosphere at unprecedented space and time scales. In addition, mesoscale models (MM5, OMEGA, NMS, RAMS, etc.) containing elaborate and comprehensive physical representations of the atmosphere and underlying surfaces are available to the scientific community for a wide variety of numerical experiments. These models are being refined for use in Antarctica, particularly for numerical weather prediction. The availability of such observational and numerical tools allows far more detailed physical process studies than ever before. Detailed knowledge of the behavior of the Antarctic atmosphere is required before questions of global change can be addressed. Given the unique and important role of Antarctica in the global

climate system, it seems essential that a comprehensive program be established with the long-term goal of documenting climate change and ultimately understanding broad scale impacts. Prerequisite to actual global change programs, detailed atmospheric process studies must be conducted to examine the interaction between the local Antarctic climate components. Given the documented global importance of the Ross Sea sector on synoptic and longer time scales and the extensive logistical support in place, it seems logical to conduct an intensive study in this region of Antarctica.

2. Outstanding Issues

a. Atmospheric variability

The atmosphere varies on a wide range of space and time scales, and this variability represents the signature of climatic phenomena on Antarctica. The variability characteristics of atmospheric circulation, cloud cover, precipitation, etc., are not well known for Antarctica because of limited analysis and uncertainties in new data sources. This knowledge is required to understand and model climate variability and change.

On the interannual time scale, the largest variability is generated by the El Nino-Southern Oscillation phenomenon, and is concentrated in the South Pacific sector of Antarctica. Figure 1 shows the snow accumulation (actually precipitation minus evaporation or P-E) calculated from the atmospheric moisture budget using the operational analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) for an area that covers most of the Ross Ice Shelf and Marie Byrd Land. P-E is strongly and positively correlated with the Southern Oscillation Index (SOI) from the early 1980s to 1990, and then switches to a strong negative correlation that persists to today. These results are primarily due to changes in the mean atmospheric circulation associated with the dominant pressure center in circumpolar trough and *not* eddy activity changes. The time-mean circulation shows anomalies that fit with the precipitation behavior. Figure 2 describes the surface pressure field anomalies during the spring preceding the peak of the strong 1997-1998 El Nino event. There is a 7-hPa low pressure anomaly in the Ross Sea and a 9-hPa high anomaly in the Bellingshausen Sea that support an enhanced northerly flow into Marie Byrd Land and yield the enhanced P-E resolved in Figure 1. The pressure anomalies affecting other parts of the Antarctic coast are much smaller, apart from that associated with 5-hPa anomaly north of the Weddell Sea. The varying high latitude response to tropical sea-surface temperature forcing must arise from some combination low latitude atmospheric and probably higher latitude oceanic influences, and is an active area of research.

The low-pressure anomaly in the Ross Sea in Figure 2 reveals a strong impact in the Ross Sea-Ross Ice Shelf area that is confirmed by the very bad operational season experienced in the 1997-1998 austral summer by the U.S. Antarctic Program. Frequent summer cyclonic activity in the Ross Sea greatly hampered air operations. This pressure anomaly would have greatly enhanced the northward flow of cold air across the western edge of the Ross Ice Shelf (discussed below) and steered it toward middle latitudes. A large impact on the big polynya located just offshore from the northwestern Ross Ice Shelf can be readily inferred. Clearly, the 1997-1998 El Nino event lead to sustained cyclonic activity anomalies in the Ross Sea sector that generated a large response that reached into midlatitudes.

b. Antarctic heat sink

The higher latitudes of the Southern Hemisphere, including the ice sheet and the surrounding sea ice zone, constitute one of the two primary areas on Earth where there is net loss of energy from the atmosphere to free space. Recent studies with global climate models (GCM) have suggested that the hemispheric and global atmospheric circulations are sensitive to modest changes in the temperature of the Antarctic atmosphere. The extent, phase, and properties of clouds play a critical role in the atmospheric heat sink, but these characteristics are poorly known for Antarctica. In a similar fashion, sea ice extent and concentration exert a major control on remote climate. When all sea ice around Antarctica was removed throughout the year and replaced by open water in a GCM simulation, the monsoon precipitation over China was substantially modified in the boreal fall.

This remote response to Antarctic forcing has been supported by an *observational* study with the National Centers for Environmental Research (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis. Figure 3a shows the correlation of August pressure over southeast Australia with the rest of the planet. Two areas of highly significant correlation are found: over Antarctica (-0.7) and over the western North Pacific Ocean (+0.7). Figure 3b illustrates the magnitude of the surface pressure change between 5 Augusts with highest pressure over southeastern Australia and 5 Augusts with lowest pressure in the same area. Large surface pressure falls are found over Wilkes Land and the Ross Sea region in association with the large pressure rises over southeastern Australia. This pressure contrast implies that the Southern Ocean westerlies are much stronger from 100°E eastward to 110°W when August pressures are high over southeast Australia. This pattern is reminiscent of the “Antarctic Oscillation”, but is linked to the tropical intraseasonal oscillation. Significantly higher pressure over the western North Pacific Ocean is associated with significant observed modulation of the monsoon precipitation over China, rather similar to the GCM sea ice sensitivity experiment mentioned above. The GCM-sensitivity experiments suggest the Pan Pacific teleconnection pattern in Figure 3b can be forced by changes in Antarctica, particularly those centered on the Ross Sea. The observational pattern exhibits a strong association with variations in tropical convection. The conclusion from observational and modeling studies is that the teleconnection is initiated by tropical forcing, but amplified by the high latitude response. It is clear from Figure 3b that the areas in and around the Ross Sea play a critical role in this teleconnection, and furthermore that enhanced outflow of cold air from the western Ross Ice Shelf into the Southern Ocean is a critical aspect of this teleconnection.

c. Topographic Forcing

The Antarctic terrain is the singlemost dominant factor in shaping the meteorology over the ice sheet and oceanic regions adjacent to the continent. The broad, high ice topography is an effective barrier to air masses impinging on the continent from the north. Physical characteristics of the ice sheet are responsible for the radiative budget near the surface and serve to strongly constrain the dynamics of the Antarctic atmosphere. South polar geography is the antithesis of that displayed by the north polar basin and is responsible for the much more extreme climatic conditions displayed by the atmosphere surrounding Antarctica.

Motion fields adjacent to the Antarctic continent are highly constrained by the ice topography. Perhaps the best-known example is the continental katabatic wind regime. These winds occur as a consequence of the radiative cooling of the Antarctic ice slopes, and are closely coupled to the behavior of the overlying atmosphere. The interaction of the katabatic component of the wind with the ubiquitous cyclonic events about the continent is important in northward transports of mass, heat and momentum, yet are incompletely understood. The topographic configuration of the continent dictates the primary pathways by which energy transports between Antarctica and the rest of the globe occur on nearly every time scale. As an example, Figure 4 illustrates the mean winter streamlines at a height of 10-m above the surface based on daily simulations using MM5 for the period 15 June to 15 July 2001. The streamlines illustrate that favored pathways of cold air transport are present at high southern latitudes, shaped by the orientation of the ice terrain and presence of the Transantarctic Mountains. An example of the topographic constraint of air streams can be seen in the sector surrounding the Ross Sea. Meridional low-level transports here are focused within a relatively narrow corridor. Unlike the case in the Northern Hemisphere, transports from Antarctica are concentrated in a few geographically preferred areas. In particular, *the Ross Sea corridor is a primary connection between Antarctica and the rest of the Southern Hemisphere.*

Diagnostic studies have revealed that export of cold air from Antarctica via the low-level wind regime can lead to large pressure changes over the continent on various time scales that vary from synoptic to seasonal. The pressure changes over the continent imply that mass must be transferred to the north. Compensating changes in the surface pressure field have been monitored to show the far field influence of Antarctic processes on the more northerly latitudes. Seasonal cycles of pressure change are clearly global in scale. Summertime mass loading over the Antarctic continent is compensated for by surface pressure decreases in the subtropical latitudes. Conversely, austral autumn is a period of strong cooling of the Antarctic atmosphere. A large continental surface pressure decrease takes place, requiring a northward mass transport and hence a pressure decrease over the continental ice slopes. Compensating pressure changes extend to the subtropics. Pronounced exchanges can occur of much shorter time periods as well. A striking example of a pressure change over Antarctica associated with a major extratropical cyclone and its impacts on the entire Southern Hemisphere is illustrated in Figure 5. The cyclonic disturbance responsible for the profound transports was situated in the Ross Sea. Strong mass flux occurs across the western Ross Ice Shelf and Ross Sea similar to that depicted in Figure 4. Figure 5 shows the impact of surface pressure changes due to this single synoptic scale process for a four-day period from 00 UTC 28 July to 00 UTC 2 July 1988. Diagnostic studies indicate that at least one-third of the mass transport was through the narrow Ross Sea corridor. Compensating surface pressure rises are seen at middle-to-lower latitudes in the Southern Hemisphere, and extend nearly to the tropics. The impact of such latitudinal mass exchanges on the circulation of entire Southern Hemisphere remains unexplored.

Effects of the low-level outflow are not limited to the surface layer. The impact of topographically-constrained continental air motions extend into the upper atmosphere and help anchor the Antarctic circumpolar vortex about the continent. This can be envisaged from the simple diagram shown in Figure 6. Low-level flows over the continent, whether katabatic or forced from synoptic processes, are among the more persistent on Earth. The near-surface

airflow is directed down topographic pathways as illustrated in Figure 4 with surprisingly little directional variation. This indicates that the atmosphere at low levels over Antarctica is strongly divergent. By continuity considerations, subsidence must take place above the Antarctic boundary layer and convergence must be found in the upper troposphere above the continent. This secondary circulation serves to generate cyclonic vorticity in the upper atmosphere and acts to anchor the circumpolar vortex about the continent. Observations show that the intensity of the circumpolar vortex about Antarctica is much stronger and much more persistent than its northern counterpart. In fact, the mean *summer* circumpolar vortex about Antarctica is approximately as strong as the mean *winter* northern circumpolar vortex. Anchoring of the vortex by the topography in effect serves to isolate the upper atmosphere to a degree not seen in the North Polar Region. The persistence of the southern vortex and differences from that in the Northern Hemisphere can be inferred from the frequency of sudden stratospheric warmings that have been documented in winter. Such conditions are common in the north but almost never seen in the southern winter. The topographic constraint on the vortex combined with the elevated ice fields permit wintertime temperatures in the troposphere to be far colder than corresponding temperatures above the north polar basin. The persistence and strength of the Antarctic circumpolar vortex, elevated ice topography and resulting physical isolation are major contributors to the well-documented springtime stratospheric ozone depletion known as the Antarctic Ozone Hole.

d. Ocean-atmosphere interaction

The radiative budget of the high southern latitudes is strongly influenced by the surface conditions. The permanent ice cover over the continent reflects approximately 80% of the incoming solar radiation. Sea ice is also critical to the radiation budget. Sea ice cover varies greatly during the year with a maximum found during September. At that time, the areal extent of the sea ice cover is 50 percent larger than the area of the continental ice sheet, thereby effectively increasing the continental area by over a factor of 2. The albedo of the entire Southern Hemisphere is sensitive to the sea ice cover and is actually higher during summer than winter. Exchanges of heat and moisture between the ocean and atmosphere are strongly modulated by the extent and thickness of sea ice. The momentum exchange between the low-level winds and ocean is important in the northward transport of ice, development of new ice and the local energy exchanges at the air/sea interface. Sea ice extent is considered a sensitive indicator of global change. Paleoclimate studies have shown sea ice extent to reach farther north during the last glaciation. The interaction between the atmosphere and ocean is highly complex and further efforts are needed to understand the very dynamic environment of the Antarctic sea ice zone. In particular, the role of extratropical cyclones in modulating changes in sea ice coverage is not well established. Coastal katabatic and cyclonic winds that are directed offshore often produce zones of reduced ice concentration. Open leads or polynyas have preferred areas of formation, such as associated with strong low-level surges of katabatic air. An example is along the northern fringe of the Ross Ice Shelf. Strong air streams from the south, such as depicted in Figure 4, frequently force an opening in the ice along a broad stretch the edge of the fixed ice shelf. The open water results in intense heat loss to the atmosphere and vigorous ice formation and which are of importance to the biota. The near-coastal ice generation and brine rejection contribute to the formation of Antarctic bottom water, the densest water in the global ocean that couples Antarctica to the rest of the planet.

In summary, Antarctica is the primary heat sink in the global climate system, and plays an important role in climate change and variability. Projections of the state of global change (e.g., global warming) must accurately account for Antarctic atmospheric processes whose effects are transmitted to the rest of the planet via the atmosphere and the ocean. In particular, the deep ocean simulations depend critically on Antarctic atmospheric conditions and they need proper physical representation in climate system models.

3. Proposed Study – Ross Island Meteorology Experiment

From preceding sections, it has been established that the Ross Sea sector, in particular, is critical in the transport of mass, heat and momentum between the Antarctic continent and middle latitudes of the Southern Hemisphere on a variety of scales. The emerging view is that this area is one of pivotal significance for global climate variability and change. Yet, a physical understanding of how Antarctic processes are linked to those over the rest of the globe is lacking on all time scales. Before climate links between Antarctica and the rest of the globe can be investigated, it will be necessary to thoroughly understand physical processes and transports over the key Ross Sea region. As a means to improve our understanding of atmospheric processes and transports within this region, the Ross Island Meteorology Experiment (RIME) is proposed. RIME is a basic and applied research program to explore in detail the atmospheric processes over Antarctica and their interactions with lower latitudes via the Ross sea sector. RIME will consist of both observational and modeling components with the *fundamental goals to study the physical processes in the lower atmosphere and transports of heat, momentum and moisture within the Ross Sea sector during episodes of extratropical cyclone forcing and accurately simulate these within numerical models.* As an additional benefit, RIME will advance short term to medium range weather forecasting in the high southern latitudes. The intent of RIME is to place Antarctic processes on the doorstep of global change that will permit a wide range of climate sensitivity studies to follow. It is believed that proper representation of Antarctic processes is prerequisite to accurate climate studies, especially since Antarctic transports are strongly tied to local topographic and mesoscale processes that are currently not resolved within GCMs. It is therefore necessary to understand local and regional processes before these effects can be assimilated into GCMs and global change issues can be considered. A series of objectives have been set for RIME that are deemed necessary before climate sensitivity issues can be addressed:

- Objective 1: To better understand key phenomena such as boundary-layer dynamics, topographic modification of synoptic and mesoscale features, cloud-radiation interactions, and moist processes accompanying episodes of cyclonic activity over the Ross Sea.
- Objective 2: To conduct detailed measurements of key physical processes in the boundary layer and free atmosphere to permit the development of accurate parameterization schemes for use within numerical models, leading to high quality simulations.

To satisfy each of these objectives, a detailed complement of observational tools and numerical model strategies must be developed as part of RIME. To start, a detailed observational network must be established to support ongoing RIME activities. An enhanced array of AWS surrounding the Ross Island region will need to be deployed. Since this region is

currently the most densely sampled section of Antarctica, only modest additional deployments will need to be made. Repositioning of several of the current AWS units may be required. Additional upper air soundings will be conducted to sample the vertical structure of the atmosphere during the field phases of RIME in the form of conventional sondes and remote sensing at a remote site. An airborne observational platform such as that provided by the NCAR C-130 and/or HIAPER will also be required to collect data near the complex topography and out over the Ross Ice Shelf and Ross Sea. Availability of a dedicated aircraft for RIME is considered essential. Extensive use will also be made of data collected by remote sensing. Both satellite-borne and ground based instrumentation such LIDAR will be employed. The next generation of satellite sensors will offer unprecedented opportunities that need to be exploited during RIME. The detailed observational array will provide a high-resolution depiction of atmospheric variables in the lower atmosphere. Finally, installation of an instrumented tower will be part of the data collection. Tower data collected will enable detailed measurements of vertical fluxes in the lower atmosphere on a fine scale. Such data will allow for unique studies of the surface boundary layer during the highly stable conditions unique to Antarctica. This has important implications in terms of numerical modeling of the Antarctic atmosphere. It is essential that energy exchanges between the surface and lower atmosphere be properly represented in atmospheric numerical models.

A major effort will be to refine physical parameterizations within models to properly portray the physics of the Antarctic boundary layer. Correct parameterization of fluxes will be a major component of the second objective and is considered vital to successful numerical simulation of local processes around the Ross Island region for which detailed measurements are available. It is believed that the success of numerical simulations will allow larger scale studies in the future to address issues pertaining to the interaction of atmospheric processes between Antarctica and the rest of the Southern Hemisphere. A fundamental goal of RIME will be to ensure accurate numerical simulation of the physical processes listed in the first objective. Numerical simulation is the instantiation of an understanding of the physical processes of a system. To the extent that a model agrees with observations, it represents a confirmation of the physical understanding and the techniques used to simulate the physical processes encapsulated in the model. Model studies thus will form an essential component in the physical understanding of the processes represented. There is an issue of scale that RIME will address. It is believed that to properly represent Antarctic processes within the context of global change, it will be necessary to understand and accurately simulate important smaller-scale forcing mechanisms. This will permit scaling of such processes within a larger-scale setting such as a GCM.

Two scales of atmospheric processes, *regional* and *local*, will be considered during RIME. These two scales will shape the experimental design of the program. The interaction of Antarctic processes with the meteorology of the subpolar latitudes of the Southern Hemisphere will require a *regional-scale* examination. The scope of RIME on this scale will encompass an area from the South Pole to approximately 65°S and from approximately 135°W to 135°E. This covers the area of most significant transport as illustrated in Figure 4 and should contain most of the significant cyclone events. Although it is through this regional-scale that Antarctica communicates with the rest of the Southern Hemisphere, strong topography modulation of the transport processes takes place along the western edge of the Ross Ice Shelf. Recognizing the importance of such interactions, a *local-scale* study will also be conducted during RIME. The

purpose of this scale will be to address the topographic modulation of atmospheric dynamics and thermodynamics associated with cyclone events and to examine the detailed vertical and horizontal structure of the atmosphere to allow enhancements in modeling activities. Much of the instrumentation will be deployed about Ross Island in pursuit of this local-scale study.

RIME is envisaged as a seven-year program. It will consist of an initial start up period (Pre-RIME or PRIME) from June 2003- June 2005 to prepare field activities by addressing key processes to be examined during RIME. This will be followed by two Antarctic field seasons, austral summer field period 2005-2006 and 2007-2008, separated by an analysis year. The final 2-1/2 years (January 2008-June 2010) will be an analysis phase. The first field season will focus on the critical austral autumn period and the second field program will examine the austral springtime transition time. Several Intensive Observing Periods (IOPs) will be conducted during each field program to monitor atmospheric processes associated with episodes of cyclone forcing. During the IOPs, the airborne observing platform will conduct extensive flight campaigns and frequent, high resolution vertical soundings will be made. Specifics of the RIME experiment can be found in the ***RIME Detailed Science Plan*** document that has been widely circulated and can be found on the web at www-bprc.mps.ohio-state.edu.

The Ross Sea sector of Antarctica is logistically accessible by the U.S. Antarctic Program, and is characterized by strong international collaborations with France, Italy, and New Zealand. Airborne sampling of clouds, chemical constituents, and circulation characteristics can be supported from the local airfields, and ship campaigns can be staged from the port. An additional benefit for conducting RIME will be higher quality forecasting support for operations in the vicinity of the Ross Sea.

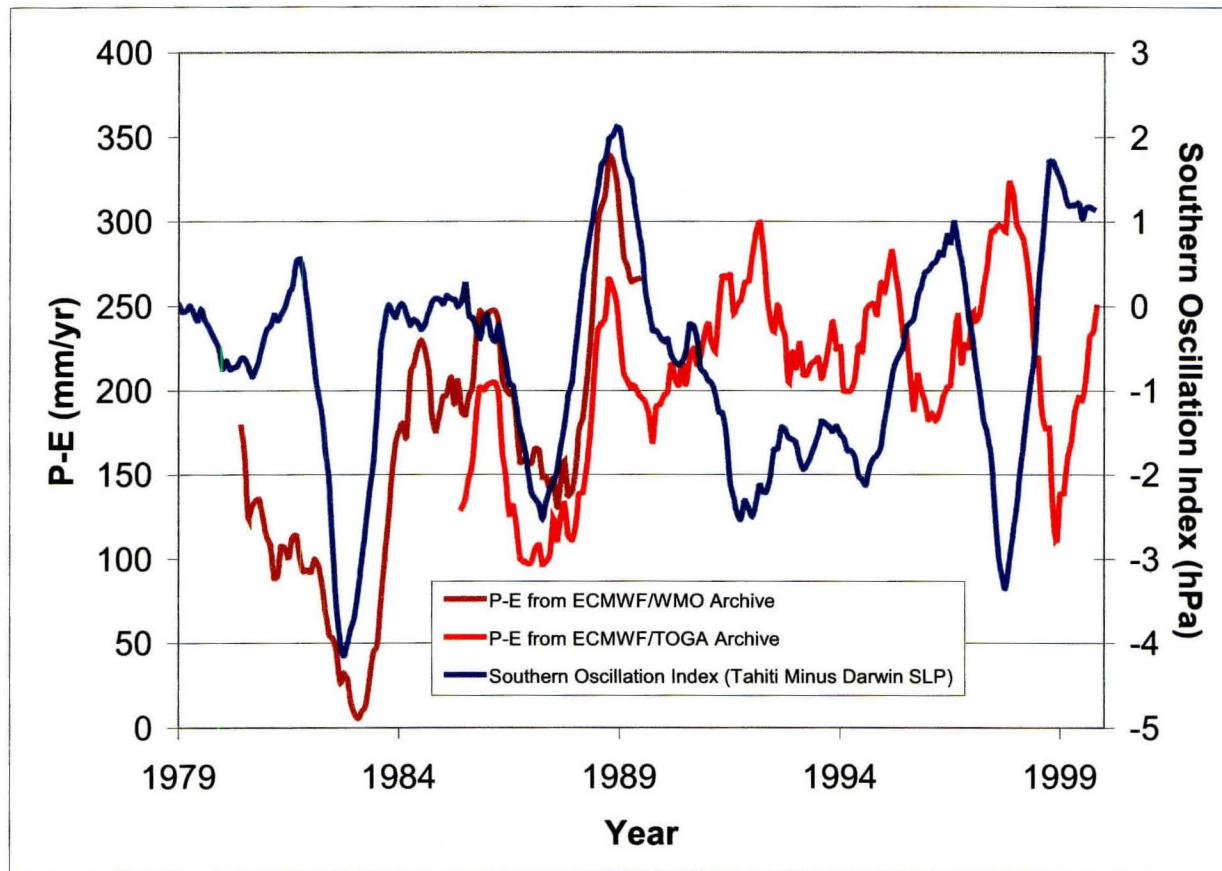


Figure 1. Comparison of precipitation minus evaporation for South Pacific Sector 120°W-180°W, 75°S-90°S and the Southern Oscillation Index (annual running means). The series are correlated from 1982-1990. After 1990, the relationship between the series rapidly switches to become anticorrelated, a relationship that exists through 2000.

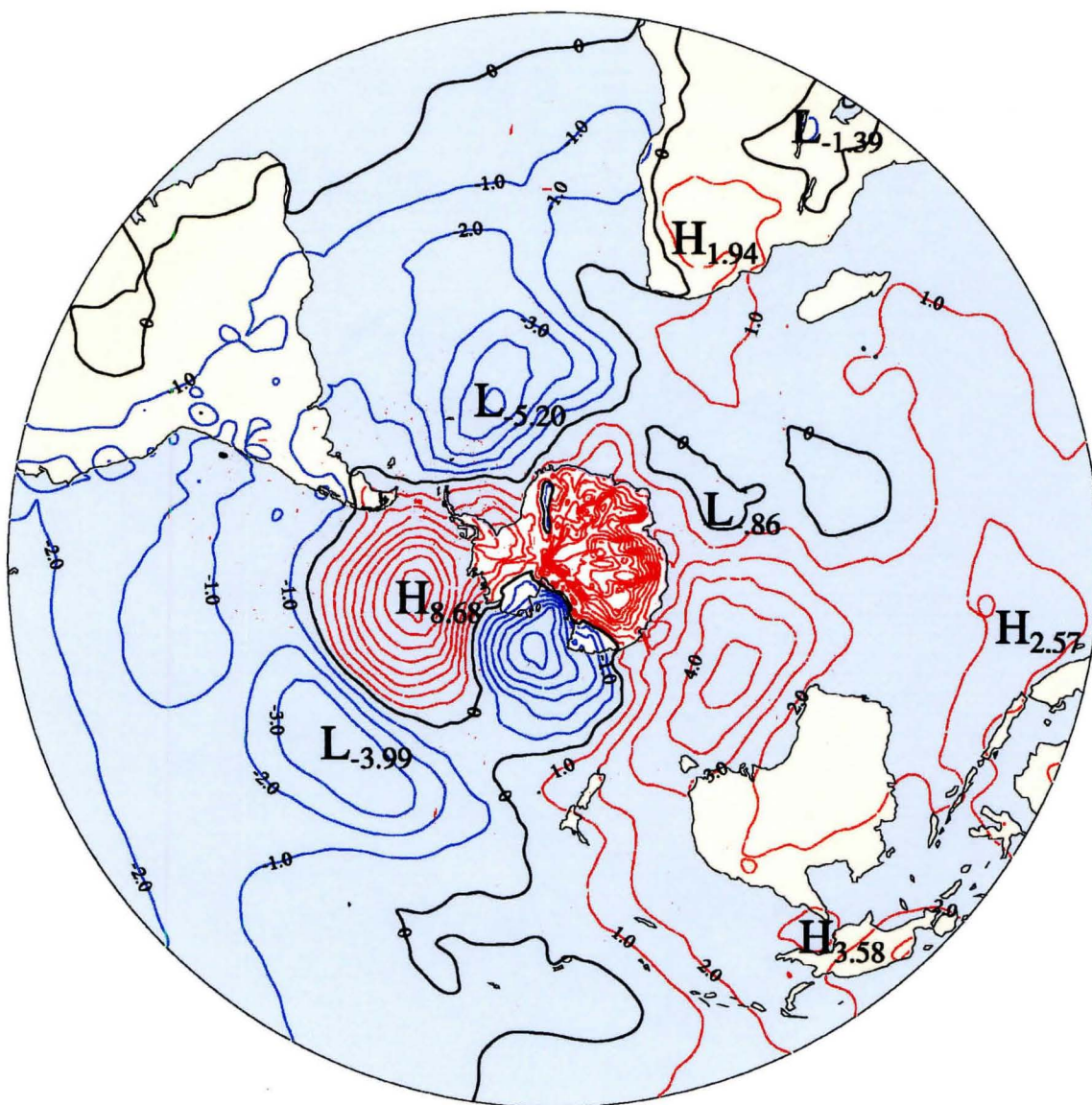


Figure 2. ECMWF/TOGA Analysis August-September-October mean sea level pressure anomaly field for 1997 departure from 1985-1999 mean. Contour interval is 1 hPa with positive differences shown in red and negative values in blue.

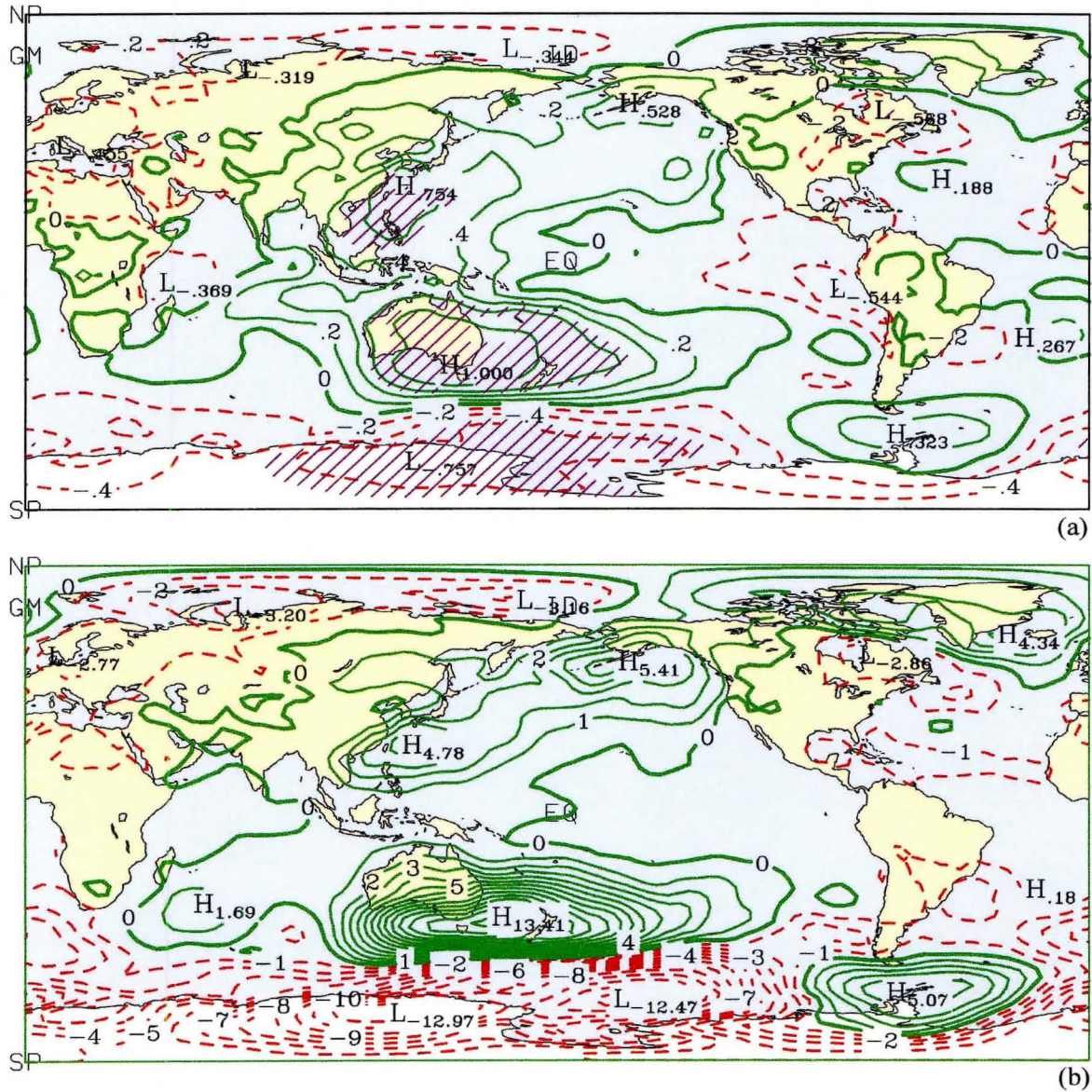


Figure 3. August teleconnection shown by (a) correlation of 1977-1998 monthly surface pressure to southeastern Australia and (b) difference in average surface pressure between 5 Augusts of above normal and 5 Augusts of below normal surface pressure for southeastern Australia. Contour intervals are 0.2 in (a) and 1 hPa in (b). Hatching in (a) shows statistical significance at the 95% confidence level.

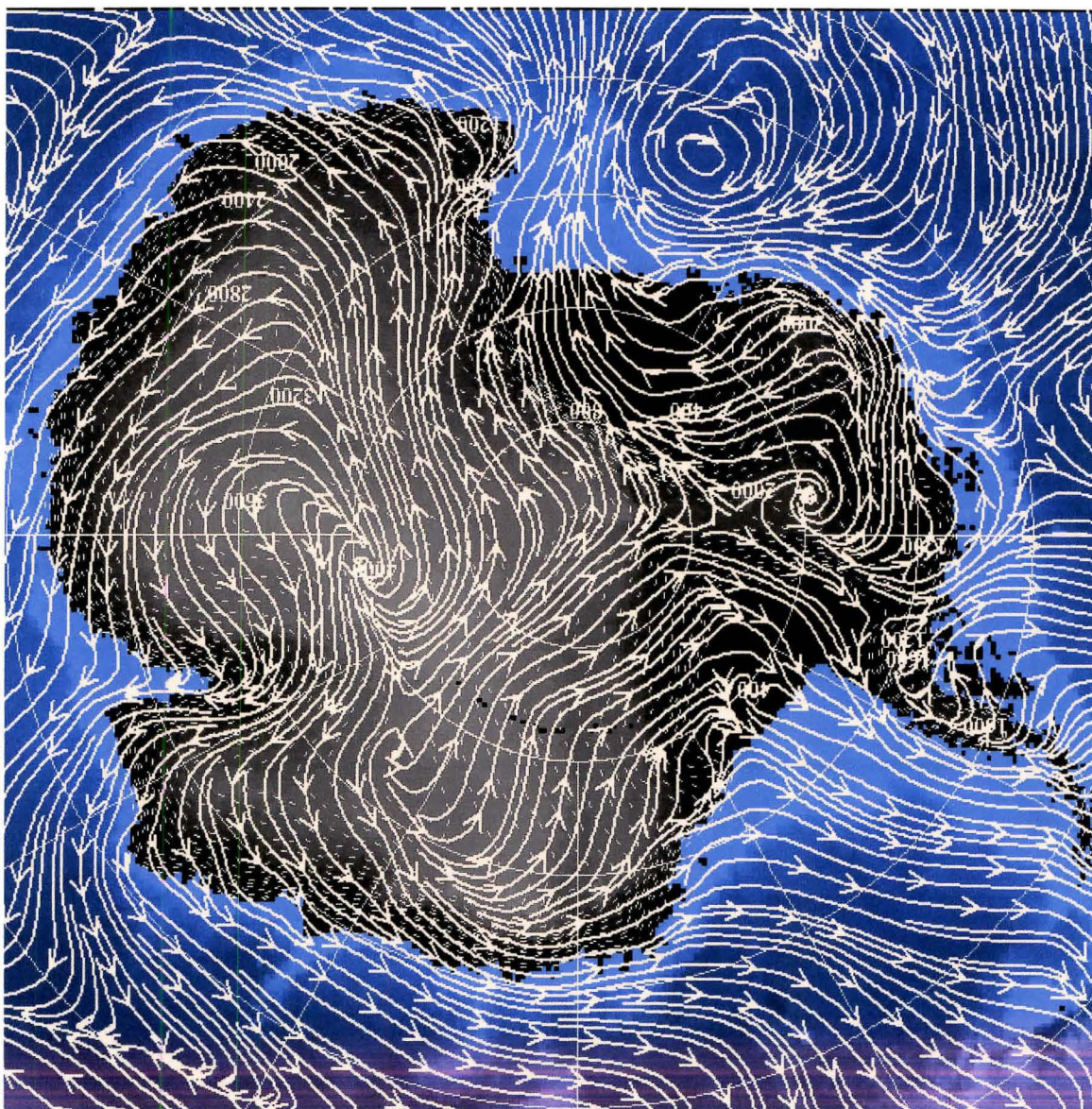


Figure 4. Mean winter streamlines of the wind at approximately 10-m above the surface based on daily MM5 simulations 15 June – 15 July 2001.

Surface Pressure Changes

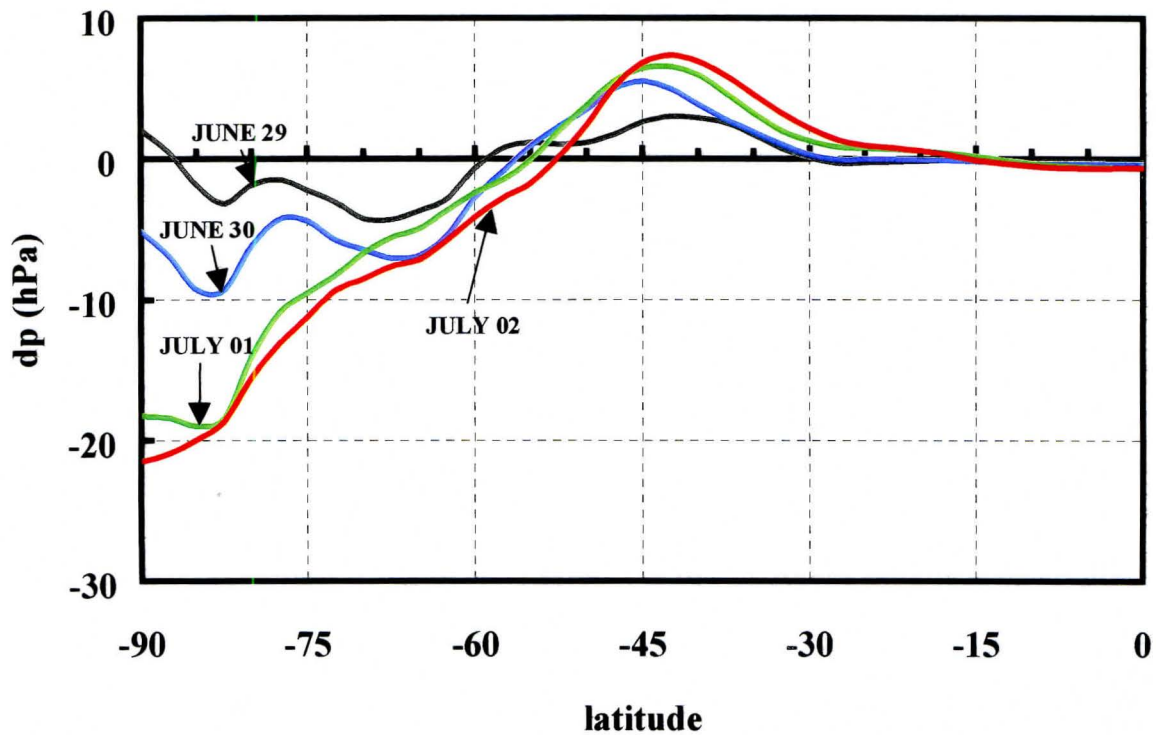


Figure 5. Zonally-averaged surface pressure differences from 00UTC 28 June 1988.

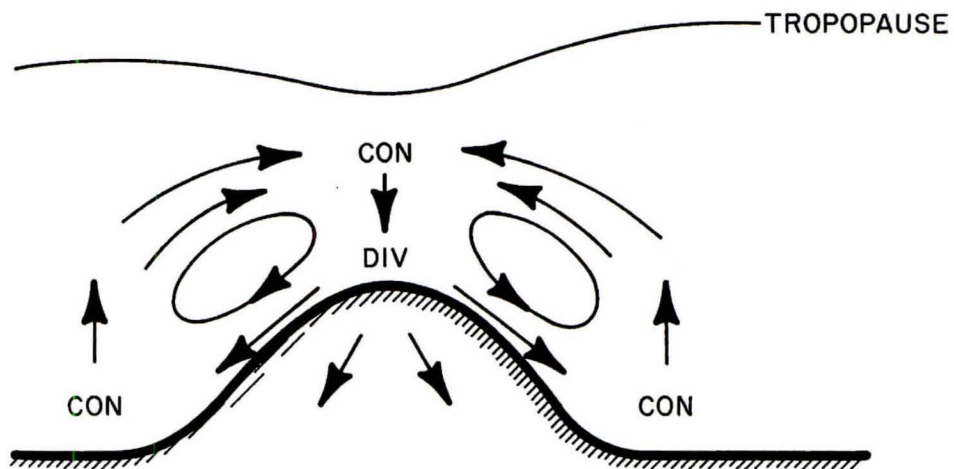


Figure 6. Schematic depiction of the secondary circulation over Antarctica forced as a result of the low-level topographically-induced air streams.